EXPERIMENTAL DESIGN FOR CONTROL
OF THE
HYDRAZINE-OXYGEN FUEL CELL

by

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UNITED STATES
NAVAL POSTGRADUATE SCHOOL

THESIS

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September 1968

ABSTRACT

The control of output voltage of an experimental
hydrazine-oxygen fuel cell is investigated. A mixture of
nitrogen and oxygen is introduced into the cathode cavity,
and the percentage of oxygen is varied to control the out-
put voltage. After dynamic testing, a typical response is
defined, and a feedback control system designed to improve
transient response. The control scheme is evaluated using
a digital computer to simulate the simplified plant model
and the controller.

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TABLE OF SYMBOLS AND ABBREVIATIONS

s	LaPlace transform operator
ω	Radian frequency
e	Natural Logarithm base
T	Fuel cell temperature
p_o	Oxygen pressure to mixing valve
p_n	Nitrogen pressure to mixing valve
p_c	Control air pressure to transducer
p_m	Gas mixture pressure to fuel cell
V_c	Control voltage to transducer
V_o	Fuel cell output voltage
t_d	Deadtime, measured from zero until output appears
t_s	Settling time, measured from zero until final value is reached
f	Gas flow rate
F_o	Open loop transfer function, general
F_c	Closed loop transfer function, general
G_{fc}	Experimental System transfer function
$\%O_2$	Percent oxygen in oxidant gas
$\%H$	Percent hydrazine in fuel
$\%E$	Percent electrolyte (KOH) in fuel
R_L	Fuel cell resistive load

ACKNOWLEDGEMENTS

1. INTRODUCTION

The use of fuel cells as a source of commercial power is becoming more of a reality each year, a consequence of increased emphasis in research. Today fuel cells are successfully being used for propulsion of slow vehicles such as heavy equipment [7.] and deep submersibles [5.]. The future use of fuel cells for propulsion application seems to be inevitable. In present vehicular application the fuel cells are arranged in banks, and used as are storage batteries; speed control is obtained by means of an electrical controller between the fuel cell output terminals and the drive motor [6.] [7.].

The idea of controlling fuel cell output voltage, and hence vehicular speed, by means of the chemical inputs to the cell, has been investigated [1.] [2.] [4.]. Tests on the hydrazine-oxygen (air) fuel cell by Powers [1.] and Rees [2.] indicate that a likely candidate for control of this type of fuel cell is the gas flow rate. Both Powers and Rees found that response time to change in gas flow for pure oxygen is very slow, but when air is used as the oxidant, delay time is such that an acceptable feed back control could be employed. Rees proposed such a system qualitatively.

Another possible candidate for controlling the output voltage is the composition of the oxidant gas. If pure oxygen and an inert gas are mixed in varying proportions, and introduced into the cathode cavity, the output voltage

increases with an increase in oxygen in the gas mixture, if gas flow rate is held constant. An experimental investigation of the reaction by the General Electric Corporation on the ion-exchange membrane fuel cell indicated that the composition of the oxidant gas was a feasible way to control the cell output voltage [4.].

To determine whether the composition of oxidant gas provides feasible control of the hydrazine-oxygen fuel cell is the objective of this experimental thesis. The output quantity will be fuel cell voltage, with a constant resistive load applied. This condition is considered analogous to that wherein the fuel cell is the source of power for a main propulsion motor, drive speed being proportional to cell voltage.

2. DESCRIPTION OF EXPERIMENTAL PLANT

The Allis Chalmers hydrazine-oxygen (air) research fuel cell was used for experimentation. This is a small, 100 watt maximum, laboratory fuel cell. Air can be used as the oxidant gas at high flow rates and pure oxygen at lower flow rates. The hydrazine (fuel) is carried in an aqueous solution of potassium hydroxide, and recirculated through the anode cavity.

In order to investigate the effect of the oxygen content of the oxidant gas, a gas mixing apparatus is necessary, such that the mixture is proportional to an electrical signal. A three-way valve positioned by a linear actu-

ator seems the logical answer; however, it was discovered that this type of valve, miniatureized for low-flow laboratory use, was unavailable. Consequently two pneumatic valves operating in tandem were used to mix the gas. The control signal goes to a current-to-air pressure transducer, and the output air pressure positions the valves. One valve controls the flow of oxygen, the other the flow of nitrogen. In this manner a gas having the desired percentage of oxygen is sent to the cathode cavity. This method of mixing the gases is far from optimum; some time delay is introduced as well as hysteresis. The time delay is small compared to the chemical reaction, but the hysteresis proved to be very troublesome, as will be discussed later.

A schematic representation of the experimental plant is shown in Figure 1. A more detailed description is contained in Appendix D, Part 1., and equipment characteristics of each component are shown in Appendix A.

As part of the Fuel Cell Laboratory at the Naval Postgraduate School, a low voltage converter was built and tested. The converter is described in Appendix A, but was not considered part of the experimental plant.

3. STATIC PLANT CHARACTERISTICS

In preparation for dynamic testing, the general performance of the fuel cell with respect to the oxidant gas composition and velocity was investigated. The load profile of the fuel cell for various amounts of oxygen is

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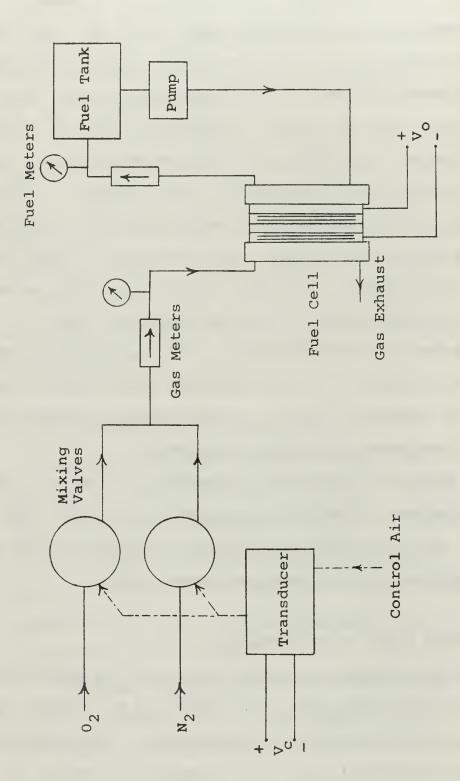
Figure 1. Experimental System

shown in Figure 2. The effect of increased amounts of oxygen is obvious. The output voltage as a function of oxygen content for various velocities is shown in Figure 3. For gas flow rates of 200 cc/min and 800 cc/min the output reaches respective maxima at approximately 75% O_2, whereas intermediate flows offer more control. Accordingly, 500 cc/min was chosen as the flow rate for frequency and transient response testing.

4.   DYNAMIC TESTING

Appendix B describes the testing procedure employed to obtain the open loop frequency and the transient response to step changes in % O_2. In these tests all plant variables were held constant and the control variable, percent oxygen in the oxidant gas (% O_2), was varied. The input to the system is the voltage (V_c) applied to the current-to-pressure transducer, which in turn controls % O_2.

a.   Transient Response

The characteristic step response of the plant is a dead time followed by an overdamped rise. The length of dead time and the shape of the overdamped rise are dependent on two factors: 1) the level of % O_2 when the step occurred, and 2) the magnitude of the step. The response curves did tend to be grouped according to the above considerations into four categories: full-range, low-range, mid-range, and high-range. Typical response behavior in each of these ranges is shown in Figure 4.

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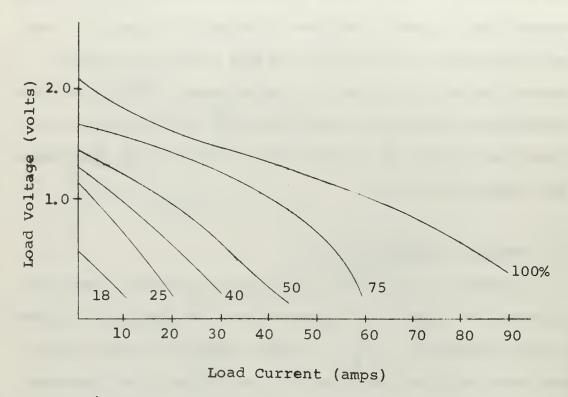
Figure 2. Load Profile at Various %O_2
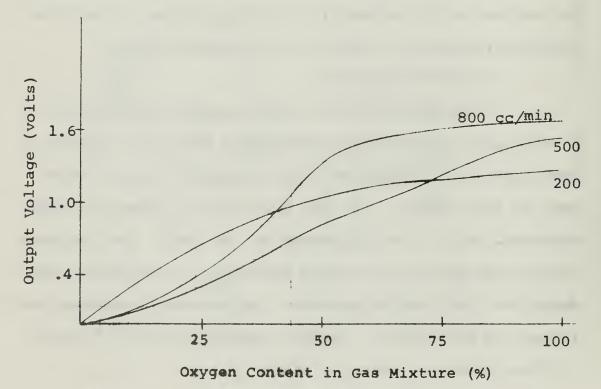
Figure 3. Load Voltage vs. %O_2 For Various Flow

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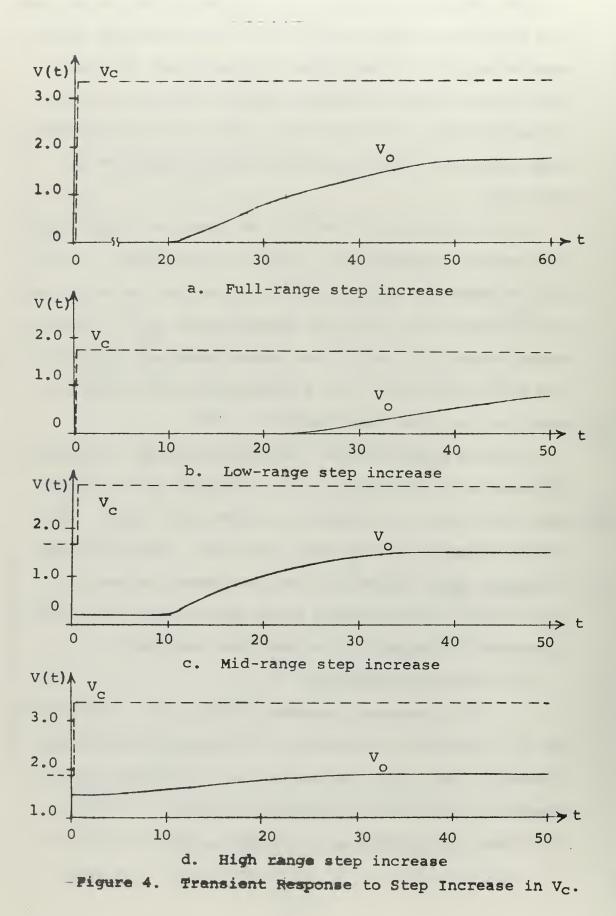
The response in each of the ranges is seen to be that of a highly over-damped system with pure transport delay. Considering the response after the dead time, the full-range and mid-range responses could be that of a linear system with two real axis poles, while the high and low range responses reflect possible multiple poles on the real axis.

It is difficult to obtain a mathematical model from the transient behavior when multiple poles exist. A graphic procedure to define the real roots for the more simple response curves has been demonstrated [11.]. The response curves 4.a. and c. are almost identical with that of a pure lag circuit, as is demonstrated in Figure 5., except at the break away point.

Typical step decrease responses are shown in Figure 6. All large step decreases in % O_2 resulted in relatively short dead times, followed by a rather fast decay. Small decrease response curves were very slow. While the step decreases again demonstrate an over-damped system, no single model could be found which approximated both the increase and decrease for the same step magnitude.

b. Frequency Response

The frequency response of fuel cell output voltage to a sinusoidal variation in % O_2 was experimentally obtained. The output voltage was not sinusoidal, but approached a sine wave at frequencies above .4 rad/sec. The output was treated as a sine-wave, however, and the

a. Full-range step increase

b. Low-range step increase

c. Mid-range step increase

d. High range step increase

Figure 4. Transient Response to Step Increase in V_C.

a. Mid-range   b. Full-range
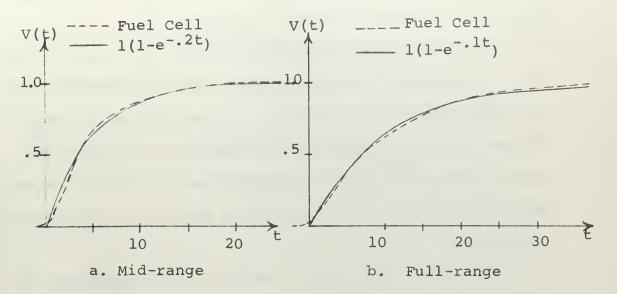
Figure 5. Comparison of Cell Response and Simple Lag
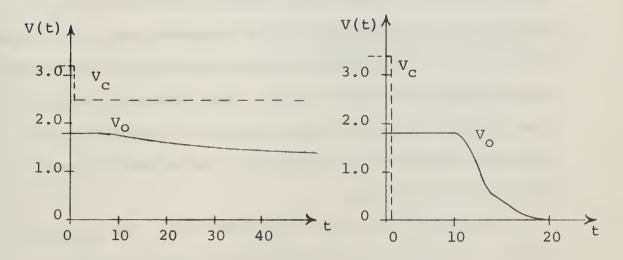
Figure 6. Transient Response to Step Decrease in V_c

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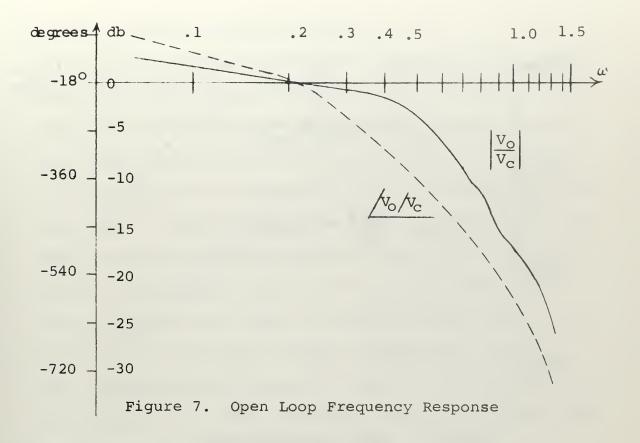
resulting frequency response curve, which is the average
for several tests, is shown in Figure 7.
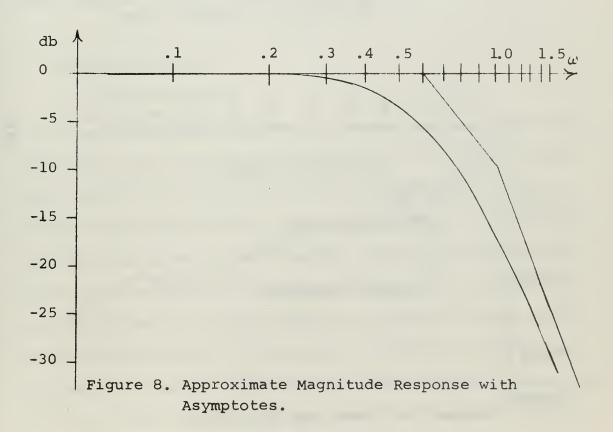
Any attempt to arrive at a transfer function by fit-
ting asymptotes to the magnitude curve is made difficult
by the system non-linearities; no asymptotes fit well.
Figure 8. shows a smooth approximation to the response
curve, along with a set of asymptotes which fit reasonably
well. The result indicates double poles at .6 rad/sec and
1.0 rad/sec.
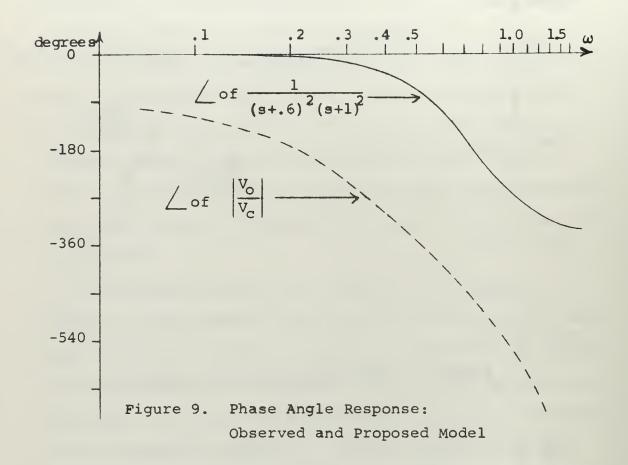
The phase angle plot of Figure 7. is reproduced in
Figure 9. along with the phase angle plot of a system with
double poles at 0.6 and 1.0 rad/sec. The transport delay
observed in transient response testing, shows up here as
phase lag. To obtain the magnitude of the lag, the phase
angle difference between the transfer function obtained
from magnitude asymptotes and the observed data, is plotted
in Figure 10. This curve is very informative; the phase
inconsistency is clearly shown: some frequency ranges
have a fixed lag (zero slope), while for others the lag
increases rapidly with frequency. The general slope of
this curve is -5.5 sec.
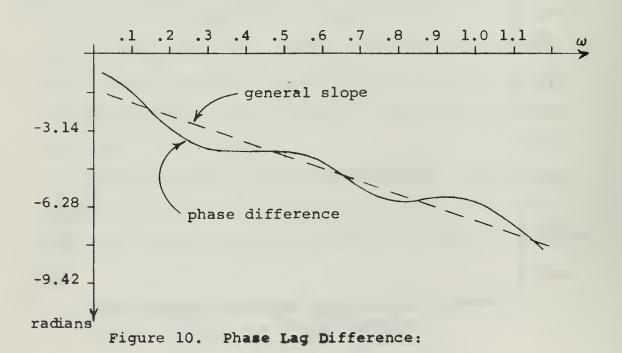
Considering the above approximations, the open loop
transfer function of the experimental plant, arrived at
from the frequency response testing, is hesitantly present-
ed:

$$G_{fe}(s) = \frac{V_O(s)}{V_e(s)} = \frac{1 \times e^{-5.5s}}{(s+.6)^2 (s+1.0)^2}$$

Figure 7. Open Loop Frequency Response

Figure 8. Approximate Magnitude Response with
Asymptotes.

Figure 9.   Phase Angle Response:
            Observed and Proposed Model

Figure 10.   Phase Lag Difference:
             Observed and Proposed Model

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c.   Comments on Dynamic Tests

Two linear techniques have been applied to the non-linear fuel cell plant, in an effort to arrive at a mathematical model. This procedure seems justified in this case, where a plant model based on differential equations is very difficult to formulate. It is not surprising, however, that no direct correlation between the frequency and transient testing results exists, and no quantitative comparison is attempted. Qualitatively, both tests demonstrate a highly over damped, non-linear system, with varying amounts of transport delay. Disregarding the time delay, both response curves can closely be modeled by a linear system with real axis poles, albeit no single linear model applies to all system responses.

5.   CONTROLLER DESIGN

a.   Considerations

The general approach to control of this fuel cell plant will be a servomechanism approach. That is, a feed back system with proportional-error compensation will be sought, such that the step input response will demonstrate desired properties. The transient responses of Figures 4. and 6. show clearly that an error compensator to best control the plant for random changes in command signal would be very complicated, if one exists. Rather, a controller composed of several compensators, each designed for part of the full range of command signals, could give satisfactory

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results. (if drive motor speed were the system output, a control input device for Stop, Slow, Moderate, Fast could "switch-in" the necessary compensator.) The remainder of this section will be devoted to the design of a controller for the mid-range, positive increase, time response.

b. Plant Definition

The mid-range plant is typified by a deadtime, t_d, of 9 to 12 seconds followed by an exponential rise with two time constants. As was previously shown (Figure 5b.) the rise is very close to that of a linear system with a single time constant, $\tau = 5$ seconds. The fact that a 1.35 volt increase in V_c produced a 1.35 volt increase in the cell output voltage is a convenient coincidence, allowing the use of unity gain. The plant to be controlled, then, is assigned the transfer function.

$$\frac{V_o(s)}{V_c(s)} = \frac{.2}{s+.2} e^{-12s}$$

c. Systems with Dead time

The control of systems with significant time delay is rather difficult. If a conventional integral derivative controller (typified by the transfer function K[s+a]/[s+b]) is employed, the effect of control action on the controlled variable is not seen until $2t_d$ seconds after the disturbance. Also the delay time introduces stability problems, which would require low gain from the controller [12.]. It has been shown, however, that if conven-

tional control is used, a simple integral controller (such as that with a transference $K/[s+b]$) gives as good a result as the best proportional integral derivative control system [13.].

An excellent approach to control of a system with dead time was developed by Smith, and is called the Smith Predictor [11.]. A general schematic of such a system is shown in Figure 11. The process to be controlled has transfer function $P(s)e^{-st_d}$, which must be measured and modeled. A minor feedback loop around the compensator, $C(s)$, contains a model of the plant without dead time, and the pulse transfer function $(1-e^{-st_d})$. The purpose of the minor loop is to predict what the system output will eventually be, and introduce this into the main loop until the actual system output appears. When it does, at time t_d, the minor loop is "switched out" by the effect of the function $(1-e^{-st_d})$. The Smith Predictor is designed for use with processes whose dominant time constant is small compared to the dead time, which is true for none of the fuel cell responses observed. In addition, the pulse transfer function is difficult to implement, and introduces significant "ripple" if t_d is incorrectly modeled or if the dead time of the plant were to vary.

A modified control scheme based on the same predictor principle is shown in Figure 12. Here the controller, $G(s)$, is designed to best control the process considered without dead time. The presence of $P(s)$ in the minor loop

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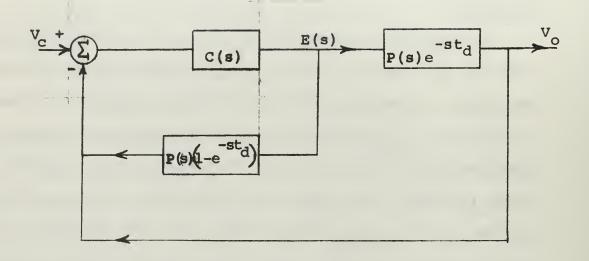
Figure 11. Smith Predictor Control System
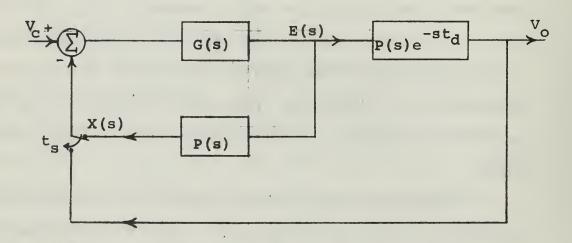
Figure 12. Modified Predictor Control System

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ensures that the control signal, E(s), is that which will
drive the actual plant to the desired response after the
dead time has elapsed. Notice that the minor feedback
signal, X(s), is the same as the plant output, except that
X(s) appears immediately. At time t_s, when the plant out-
put has reached steady state, the predictor loop is re-
moved from the circuit with a mechanical switch. A dis-
cussion of this scheme applied to the fuel cell system is
presented in the following section.

6. COMPUTER SIMULATION OF CONTROLLED PLANT
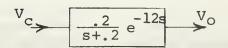
The implementation of the predictor control system is
straight forward. A compensator, G(s), is designed to ob-
tain the desired results from the plant without dead time,
P(s), in a unity feedback system. Appendix C. presents
calculations used to arrive at a simple integral control-
ler, one of several that could be used. Referring to Fi-
gure 12, E(s) must have some overshoot, since a fast rise
time in the output is desired after t_d. In the gas mixing
system used, considerable hysteresis was unavoidable; thus
the overshoot in E(s) forced the mixed gas into a saturated
O_2 condition, and unsatisfactory results were obtained.
Also, the performance of the fuel cell used for experimen-
tation changed radically at this time. An extremely high
gas flow rate (1200cc/min) became necessary, and maximum
output voltage fell to 1.35 volts. This condition was
apparently due to oxidizing of the N_2H_4 electrode, and the

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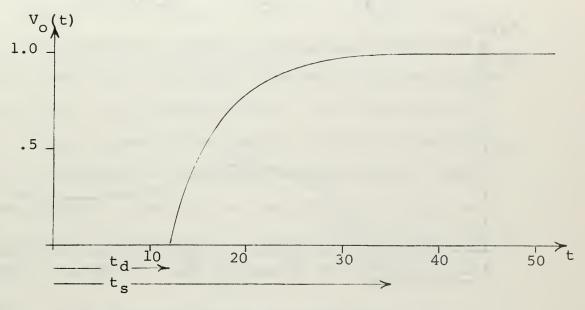
testing results obtained earlier could not be reproduced.

For the above reasons, the predictor control system could not be tested on the actual fuel cell plant, and it was necessary to model the mid-range plant and the control system on the digital computer, IBM-360. The continuous system was solved using discretized approximations for the derivatives; the computational difference equations are developed in Appendix C.

The transient response of output voltage, $V_o(t)$, for a step increase in V_c, for the uncontrolled and predictor controlled plant, is shown in Figures 13a. and b. The steady state value, .833 volts, occurs at t_s = 19 seconds for the controlled plant as opposed to 37 seconds uncontrolled. The steady state error of .167 volts could be improved on with a more sophisticated compensator, $G(s)$.

For purposes of comparison, Figures 13c. and d. show the system step response for unity feedback alone and that for a conventional integral controller. In both cases, the steady state error is large since over-all gain must be low to prevent oscillations. The conventionally controlled system is seen to have a settling time of 23 seconds, which compares well with the predictor control system. The conventional controller is certainly easier to implement than the predictor system, since the minor loop is not necessary. The design of the compensator in the conventional case is not easy to arrive at, however, since linear methods cannot be used. The compensator shown in Figure 13d. was

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a. Response of Uncontrolled Plant

b. Predictor Controlled Plant

Figure 13. Computer Simulated Response Curves

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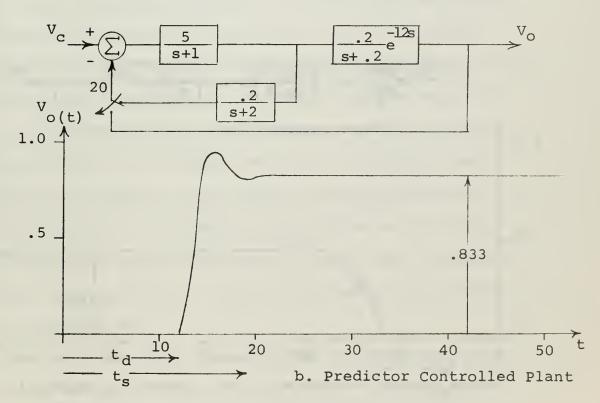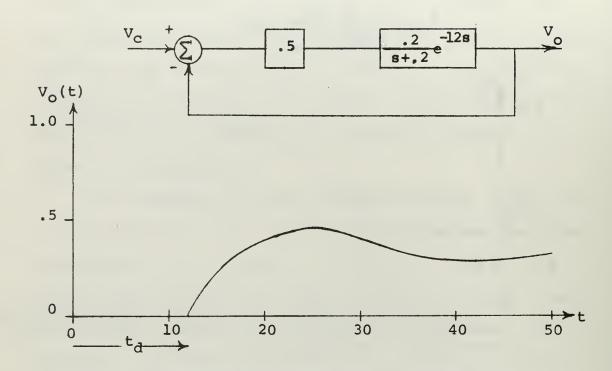
c. Unity Feedback with Fractional Gain

d. Convention Controller

Figure 13. Computer Simulated Response Curves

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arrived at by trial and error
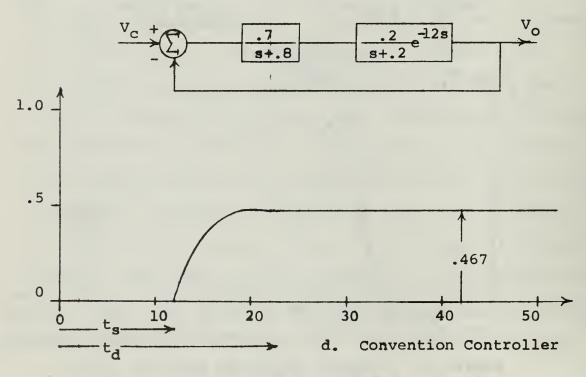
7. SUMMARY AND CONCLUSIONS

The hydrazine-oxygen fuel cell is seen to be respon-
sive to changes in the oxygen content of the oxidant gas.
When $\%O_2$ was used as the control variable, the fuel cell
system was seen to be non-linear, demonstrating over-damped
characteristics, and transport delay. The transient re-
sponse to step changes in the control variable is depend-
ent on the magnitude of the change and the initial condi-
tion when applied. However, the characteristic response to
any step change is consistent: a period of no change fol-
lowed by an overdamped rise composed of two or more time
constants.

One such response, defined as the Mid-range Response,
was chosen to investigate controllability of the system.
Two control systems, a conventional proportional error inte-
gral controller, and a predictor control system were both
seen to yield satisfactory settling times after the dead
time had elapsed. No attempt was made to find the "best"
controller; the quantitative results show the merits of
each scheme. Due to equipment difficulties no controller
could be applied to the experimental plant, and a computer
simulation had to suffice. This is not believed to detract
from the conclusions.

The results of this investigation indicate that con-
trol of the output voltage by varying the composition of

the oxidant gas is feasible for applications where rather
long settling times are acceptable. Any controller employ-
ed would be complicated by the fact that the response is
not identical throughout the range of operation.

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APPENDIX A

AUXILIARY EQUIPMENT CHARACTERISTICS

1. Current-to-Pressure Transducer

The current-to-pressure transducer is a Foxboro Model 69TA-1 Style B [10]. Field calibrations can be made to adjust the input current signal over a wide range; the output range is normally 3-15 psig with an input air pressure of 20 psig. Several available input-output characteristics are shown in Figure A1.A schematic is shown in Figure D3.

2. Gas Mixing Valves

The valves used to mix nitrogen and oxygen are pneumatic controlled needle valves, Foxboro Type V4, which are compatible with the transducer; that is the full range of travel results with an air signal of 3-5 psig. The flow curve of these valves is shown in Figure A2. The approximate equation for flow capacity, $C_v = 7.9Q[1/(p_1-p_2)p_2]^{1/2}$, where Q is flow in cc/min, was used to size the valves. Both valves have $C_v = .0052$, thus the maximum flow can be varied by choosing the input and discharge pressures. By adjusting the input pressures of O_2 and N_2 separately, and choosing a particular transducer calibration curve, the gas mixing characteristic shown in Figure A3. was arrived at. This curve was plotted from data obtained on a Gas Partitioner (Fisher-Hamilton Model 29). The hysteresis, due to static friction in the diaphram positioning mechanism, is unfortunate but unavoidable. For this reason, this method of mixing O_2 and N_2 proved to be a poor choice. The flow
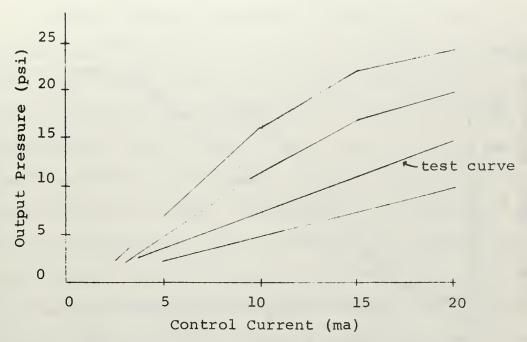
Figure A1. Current-to-Pressure Transducer
Characteristic
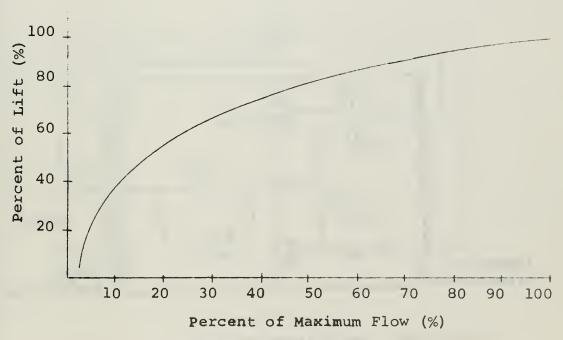
Figure A2. Needle Valve Characteristic

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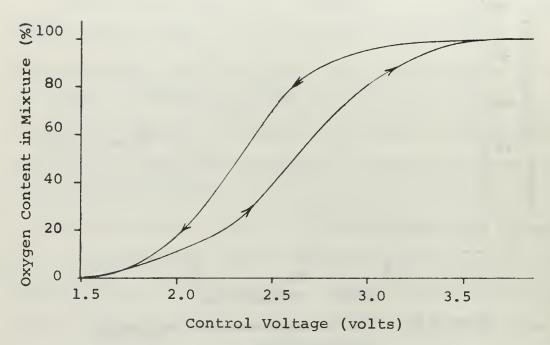
Figure A3.   Gas Mixture Characteristic
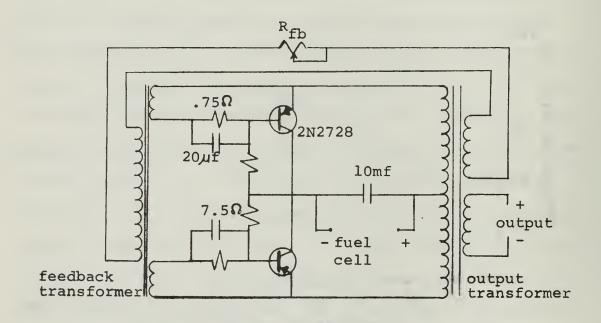
Figure A4.   Low Voltage Converter

rate of the mixture is constant for all values of % O_2.

3. Low Voltage Converter

A dc-dc converter specially designed for solar, thermo-electric, and fuel cells by Motorola Semiconductor Products Inc. [14] was built for the fuel cell laboratory. The circuit diagram is shown in Figure A4. A high efficiency is possible with this converter due to the use of two parallel wound switching transformers, and power transistors having low saturation voltage. The frequency of oscillation is set by adjusting R_{fb}, which determines the feedback voltage. The voltage output is a square wave, which was converted to d.c. using a bridge rectifier (not shown). The efficiency of this converter varies slightly with output power; between 50 and 80 watts, the efficiency is approximately 70%.

APPENDIX B

DYNAMIC TESTING PROCEDURES

In order to study the effects of % O_2 as a control variable all other variables must be maintained constant. To facilitate this a "Dynamic Testing Procedure" was established for all tests. This fixed condition was used for all tests:

Percent hydrazine in the fuel mixture,   % H = 10

Percent potassium hydroxide in the

fuel mixture,   % E = 33

Fuel temperature, $T = 68^O F$

Pressure of gas mixture to the cell, P_m = 4 psig

Flow of gas mixture to the cell,   f = 500 cc/min

Pressure of O_2 to O_2 throttling valve, P_O = 85 psig

Pressure of N_2 to N_2 throttling valve, P_n = 35 psig

Pressure of control air to transducer, P_c = 17 psig

Transducer calibration (5-25 ma,

6   - 13 psi),   (See Figure A3)

Fuel cell fixed resistive load, R_L = 5 ohms

1. Frequency Response

The following procedure was followed in obtaining information for the fuel cell plant open loop frequency response:

a. Record any deviation from Testing Procedure.

b. Bias the control voltage, V_c, at 2.55 volts and set the sine wave generator amplitude to .85 volts.

This biases % O_2 at 45 and results in a peak-to-peak swing 5 to 95% O_2.

c. Record on trace recorder the input and output voltage while varying the frequency from .1 to 1.4 radians/second. Calculate the magnitude in decibels, 20 log(V_o/V_c), and the phase lag in degrees.

2. Transient Response

The transient response to step changes in control voltage was obtained in the following manner:

a. Record any deviation from Testing Procedure.

b. Set control voltage at 1.35 volts, corresponding to % O_2 of zero.

c. Record input and output voltage on the trace recorder for .35 volt steps until 3.8 volts is reached (100% O_2) then step decreases in the same fashion. Next record .7 volt step increases and decreases. Finally, record 1.35 to 3.8 volt step increase and decrease.

d. Classify the resulting response curves according to dead time and shape of response.

APPENDIX C

SUPPORTING CALCULATIONS

1. Design of Predictor Compensator

The compensator of the predictor control system is
that one which "best" controls the model plant considered
without dead time, as discussed in Section 5.c. A simple
integral controller is chosen since it will give the re-
sponse a fast rise, slight overshoot, and acceptable
steady state error. That is, a compensator of the form

$$G(s) = \frac{K}{s + \alpha}$$

will be found, using root locus techniques.

The open loop transfer function will have the form

$$F_0(s) = \frac{K \times .2}{s^2 + (\alpha + .2)s + .2\alpha}$$

and the closed loop transfer function for unity feedback is

$$F_c(s) = \frac{K \times .2}{s^2 + (\alpha + .2)s + .2(K + \alpha)}$$

Setting the denominator equal to zero, we have the locus
equation

$$\frac{Z}{s^2 + (\alpha + .2)s + .2} = -1 \text{ where } Z = .2K$$

We know that α must lie to the left of .2 so that the re-
sponse will have a rapid rise. Considering this, several
values of α are plotted on the root locus plot of Figure C1,
with the corresponding loci. Referring to a set of second-

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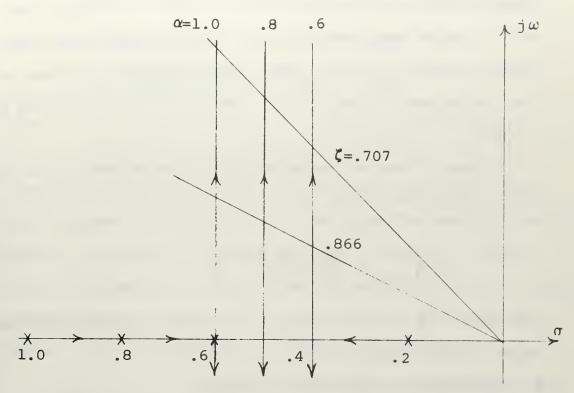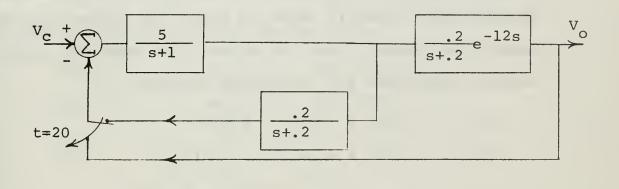
Figure Cl. Quadrant I of Root Locus
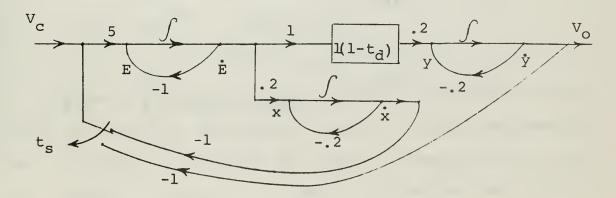
Figure C2. Predictor System Diagrams

order curves, ζ can be selected to give the desired respon-
se.   In this case, settling time is very important, thus a
rather large ζ will be needed.   Selecting $\alpha = 1.0$ was ra-
ther aribitrary.   Then if $\zeta = .866$, Z = 1.0, resulting in
K = 5.0.

Since, from the relation $F_c(s)$, the steady state value
for a unity step input is

$$v(t)\Big|_{t=\infty} = \frac{K \ x \ .2}{.2(K + \alpha)}$$

the choice of K = 5.0 and $\alpha = 1.0$ result in a steady state
value of .833 volts.

2.   Development of Computer Program

A block diagram of the predictor control system and
the mid-range plant is shown in Figure C2, along with the
signal flow graph.   From the signal flow graph the state
variable equations are written as follows:

(1) $\qquad \dot{E}(t) = -E(t) + 5 \ D(t)$

(2) $\qquad \dot{x}(t) = -2x(t) + .2 \ E(t)$

(3) $\qquad D(t) = \begin{cases} V - x(t) & , \quad t < t_s \\ V - y(t) & , \quad t \geq t_s \end{cases}$

(4) $\qquad \dot{y}(t) = \begin{cases} 0 & , \quad t < t_d \\ -.2y(t) + .2E(t-t_d) & , \quad t \geq t_d \end{cases}$

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Using equation (1) as an example, we approximate the dif-
ferential equation with the difference equation

$$\frac{E(t + \Delta t) - E(t)}{\Delta t} = - E(t) + 5D(t)$$

then

$$E(t + \Delta t) = (1 - \Delta t) E(t) + 5 \Delta t D(t)$$

Thus the continuous system can be approximated by a dis-
crete system with N equally spaced time increments: $t = k\Delta t$,
where $k = 1,2,3......,N$ and the final time is $T = N\Delta t$.
Settling time and the dead time become $t_s = k_s\Delta t$, $t_d = k_d\Delta t$
respectively.

Making these substitutions, equation (1) becomes

$$E(k\Delta t + \Delta t) = E(\Delta t[k+1]) = (1 - \Delta t) E(k\Delta t) + 5\Delta t D(k\Delta t)$$

Using the normal notation where k replaces $k\Delta t$, the
discrete equations of the system become

$$E(k + 1) = (1 - \Delta t) E(k) + 5\Delta t D(k)$$

$$x(k + 1) = (1-.2\Delta t) x(k) +.2\Delta t E(k)$$

$$D(k) = \begin{cases} V - x(k) & , \quad k < k_s \\ V - y(k) & , \quad k \geq k_s \end{cases}$$

$$y(k+1) = \begin{cases} 0 & , \quad k < k_d \\ (1-.2\Delta t)y(k) + .2\Delta tE(k-k_d) & , \quad k \geq k_d \end{cases}$$

These are the computational equations necessary to pro-
gram the system on the digital computer. This same develop-
ment was used to arrive at the computer simulations for all
the results of Figure 13. A sample program for the predic-

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tor control system is shown below. Time increment, Δt, was .05 seconds; therefore, to observe 50 seconds of response, N = 1000. Since dead time is 12 seconds, and settling time 20 seconds, k_d = 240 and k_s = 400.

Sample Computer Program:

```
      V = 1.0
      E(1) = 0.
      D(1) = 0.
      X(1) = 0.
      Y(1) = 0.
      DO 10 K = 1,1000
      E(K+1) = (1.-DELT)*E(K) + 5.*DELT*D(K)
      X(K+1) = (1.-.2*DELT)*X(K) + .2*DELT*E(K)
      IF (K.GE.240) GO TO 1
      Y(K+1) = 0.
      GO TO 2
    1 Y(K+1) = (1.-.2*DELT)*Y(K) + 5.*DELT*E(K-239)
    2 IF(K.GE.400) GO TO 3
      D(K+1) = V - X(K)
      GO TO 10
    3 D(K+1) = V - Y(K)
   10 WRITE (6,90) K,Y(K)
   90 FORMAT (T7, I4, T15, F5.3)
      DELT = .5
      STOP
      END
```

APPENDIX D

OPERATING INSTRUCTIONS FOR THE
FUEL CELL RESEARCH SYSTEM

D1. <u>System Description</u>:

The Allis-Chalmers Model 100H Laboratory Fuel Cell accepts gaseous oxygen into the cathode cavity and aqueous hydrazine into the anode cavity. Oxygen is supplied from compressed tanks and hydrazine solution (hereafter called fuel) is circulated through the anode by a variable speed pump. The cell output is low voltage direct current; reaction by-products are heat, gaseous nitrogen, and water, which collect in the fuel tank. The output power is 100 watts maximum, and insufficient to supply auxiliary equipment; 115 volt, 60 cycle a.c. is provided for this purpose.

The fuel cell laboratory is conveniently broken down into the following systems and components:

> Gas system piping
>
> Current-to-air transducer
>
> Gas mixing system
>
> Fuel system piping
>
> Fuel pump and heater circuit

Figures D1 through D4 show each system in detail and are considered to be self explanatory except for the following comments.

> a. <u>Gas system flexibility</u>. Considerable flexibility is built into the gas system to allow for the conduct of a variety of experiments. Basically, four

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gas inputs are available: air, oxygen, mixture of
air and oxygen, mixture of nitrogen and oxygen.
When air is the input it must be bubbled through
the air scrubber to remove carbon dioxide. For
all other inputs, the scrubber is by-passed. When
air or oxygen is the input, the gas may be passed
through the transducer; this makes the pressure
to the cell controllable by a d.c. current signal;
If the transducer is by-passed, the pressure is
controlled by a pressure regulator. When a gas
mixture is desired, control air is supplied via
the transducer to the pneumatic throttling valves
(hereafter called "mixing valves") and thus trans-
ducer input current controls the gas mixture. For
all gas inputs the rate of gas flow through the
cell is determined by the input pressure and the
setting of the throttling valve (Gas Flow Valve)
located on the downstream side of the cell. Exhaust
from the cathode cavity is bubbled through a dilute
solution of acetic acid to neutralize any hydroxyl
vapors which may be present.

b. Fuel system. The fuel mixture consists of liquid
hydrazine (N_2H_4) mixed with potassium hydroxide
(KOH), which acts as a circulating agent, and wa-
ter. One of the features of this cell is the wide
range of hydrazine concentrations which can be
used. As mentioned, water is a by-product of the

cell reaction causing the fuel to become diluted during operation. Also hydrazine is depleted by the anode reaction. As a result of these two effects the hydrazine concentration in the fuel is continually being reduced, requiring the occasional addition of hydrazine, and periodic batch changing of the fuel.

Although heat is produced by the cell reaction, it is insufficient to raise the fuel to the best reaction temperature. Thermostat controlled heaters are installed on the bottom of the fuel tank and a panel light indicates when the thermostat has cut on. The temperature of the fuel can be set at any desired level. On top of the fuel tank is a solenoid drain valve; when the fuel pump is secured, this is deenergized, allowing the fuel lines and the cell to drain into the tank. Also located on top of the fuel tank is a 2 psi relief valve which lifts when nitrogen gas, produced at the anode, builds up in the fuel tank. This is exhausted into a beaker containing dilute acetic acid.
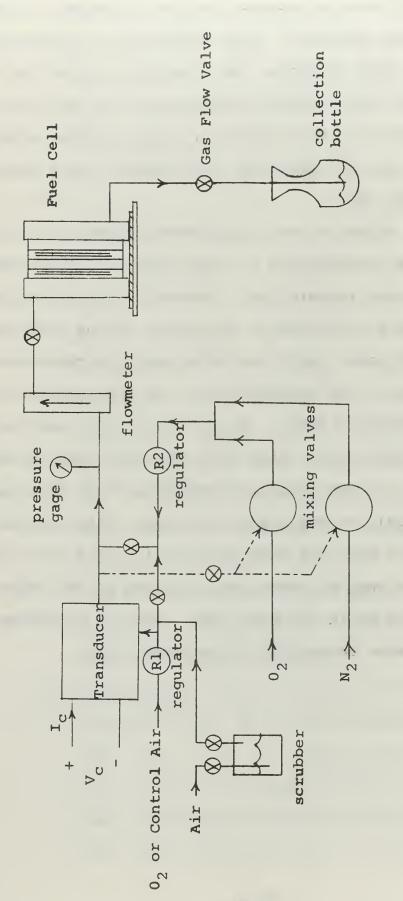
Figure D1. Gas System Piping
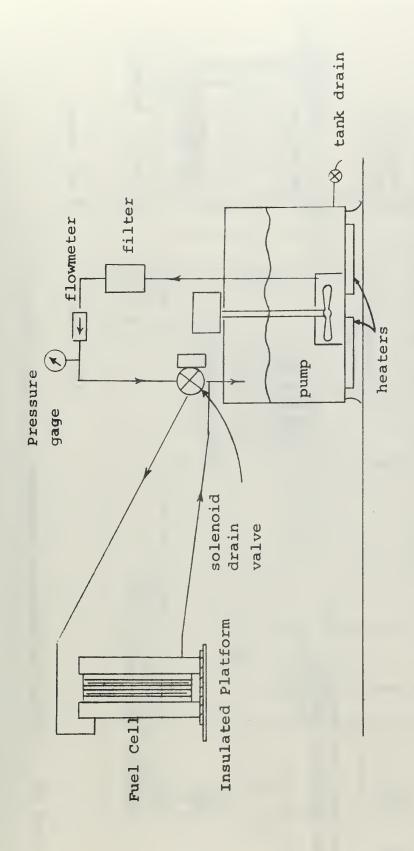
Figure D2. Fuel System Piping

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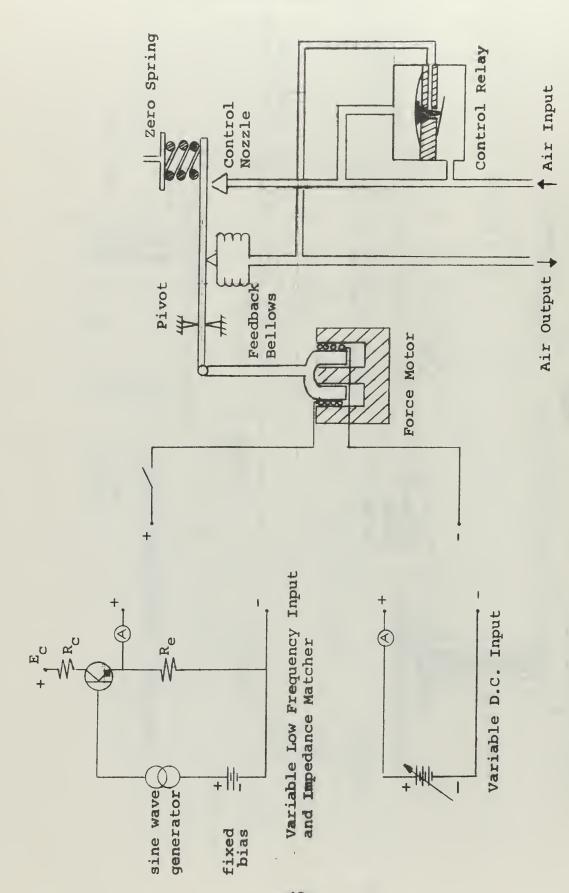
Figure D3. - Current-to-Pressure Transducer and Input Circuits
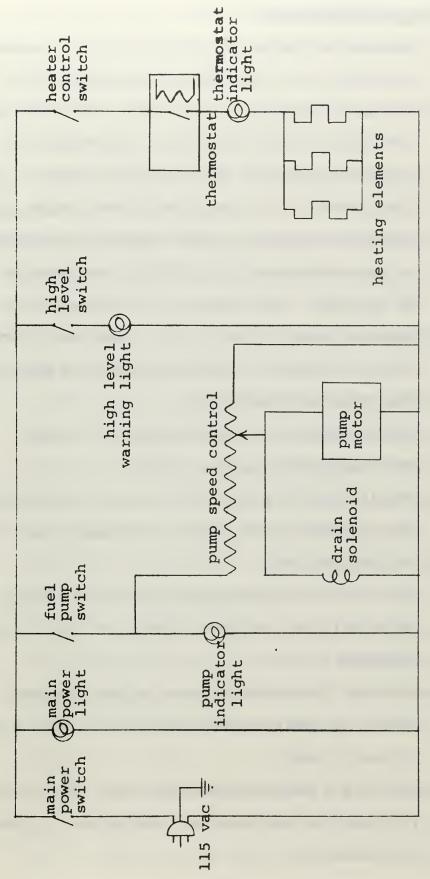
Figure D4. Auxiliary Power Circuit

D2. Light-off Procedure:

 a. Be familiar with all system circuitry, operating procedures and the instruction manual. [9] Read the last entry in the Operation Log and determine the status of the fuel batch and whether or not proper maintenance has been carried out. Locate the system in an open or well ventilated space. STANDARD ELECTRICAL SAFETY PRECAUTIONS PROMULGATED BY THE DEPARTMENT OF ELECTRICAL ENGINEERING SHOULD BE OBSERVED. SEE SECTION D OF APPENDIX III FOR CHEMICAL SAFETY PRECAUTIONS. WARNINGS CONCERNING CARE IN HANDLING COMPRESSED GASES ARE CONTAINED IN THE OPERATING PROCEDURE.

 b. Locate required gas bottles next to stand.

 c. Put wheel brakes on the stand.

 d. Put all switches on front panel in OFF position.

 e. Put auxiliary panel switch and main power switch in OFF position.

 f. See that fuel tank scrubber bottle is about one third full of a dilute solution of acetic acid (vinegar).

 g. See that the oxygen source output byproduct collector is about one third full of a dilute solution of acetic acid.

 h. See that a bottle of dilute acetic acid solution (vinegar) is available to neutralize any KOH or N_2H_4 spills.

i. See that rags, paper towels, a screwdriver and an adjustable wrench are available to correct any leak which could develop.

j. See that the table is clear of all unnecessary equipment.

k. If air scrubber is to be used, determine if it contains any 45% KOH solution. If not, fill to no more than one inch from the bottom. If the solution has not been replaced for the past ten hours of operation, replace it.

l. See that all valves are placed in the CLOSED or OFF position.

m. Connect the gas bottle hose to the desired input. CAUTION. HANDLE COMPRESSED GAS WITH CARE.

n. Arrange the test equipment required on the middle shelf, plug it into the auxiliary power panel, and make necessary wiring to the front panel.

o. Make the required fuel cell connections to the fuel cell output terminals.

p. Check the level indicator on the fuel tank. Look at the Operation Log, determine whether or not a fuel batch is in the fuel tank. If so, determine its age and whether or not to replace the fuel batch.

q. If the fuel batch requires only the addition of more hydrazine, unscrew the filling plug and insert a glass or stainless steel funnel. Measure

the required amount of hydrazine solution and pour it carefully into the funnel. DANGER. HANDLE HYDRAZINE CAREFULLY. Replace the filling plug.

r. If the fuel batch requires total replacement, mix a new fuel batch. Drain the old batch using the fuel tank drain valve. DANGER. HANDLE FUEL SOLU-TION CAREFULLY. Neutralize the old fuel batch with dilute acetic acid before disposing of it. Carefully pour in the new fuel batch. Two liters is the minimum necessary for porper pump suction. Make sure the fill plug is still connected to the tube leading to the fuel tank scrubber.

YOU ARE NOW READY TO BEGIN THE EXPERIMENT

a. Plug in the system to a 115 volt, 60 cycle source. Turn on the main power switch (middle shelf, right hand side) and the auxiliary panel switch (middle shelf, left hand side). Observe red indicator lights on the outlet panels.

b. Set up valves as necessary to provide the gas in-put desired. Activate the transducer control cir-cuit if it is to be used. Make sure you know where your prime method of gas pressure control is.

c. Make sure the gas tank regulator valve is backed out. Crack the main valve on the gas tank, ob-serving the tank pressure. Screw down on the re-gulator, adjusting for about 25 psig to the Re-search System Input.

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d. Open the oxygen source output valve all the way. Adjust the main pressure control to permit gas to flow through the fuel cell. Observe residual moisture being purged from the cell. As soon as most moisture is removed, adjust the Gas Flow Valve to an output orifice which will give the desired flow rate. A reading of 6-8 on the flow meter should be obtained for a gas pressure of 4 psig. See the Instruction Manual. [9]

e. Turn the motor controller to full voltage (full clockwise). Put the pump motor switch to the ON position. Observe motor shaft turn. Note the fuel pressure and flow rate. The pressure must not go over 5 psig. The flow rate should attain a reading of at least 6 on the flowmeter. If these conditions are not satisfied, turn off the motor and consult the Instruction Manual. LEAKS ARE DANGEROUS. IF LEAKING, TURN OFF MAIN POWER AND REPAIR. After turn on, the motor controller can be adjusted to change the flow rate.

f. Turn the fuel tank heater switch to the ON position. Adjust the thermostat to provide the desired heating. BE CREFUL NOT TO BACK THE KNOB OUT TOO FAR. [9]

g. The fuel cell should now have an output. Turn the voltmeter selector to read the voltage across one set of cell pairs, then both cell pairs.

h. Proceed with the experiment. FOR ANY EMERGENCY,

THREE STEPS ARE REQUIRED TO KILL ALL POWER.

1) MAIN POWER SWITCH OFF.

2) GAS TANK MAIN VALVE CLOSED.

3) FUEL CELL LOAD SWITCH OFF.

D3. Shut-Down Procedure:

    a. Remove the load from the fuel cell by turning the load switch to the OFF position, or by removing the load leads from the fuel cell output terminals. CAUTION. If the fuel cell is operating at high power, the load switch should be used to prevent arcing.

    b. Turn the fuel pump motor switch to the OFF position. Put motor control variac to full voltage position. Observe the fuel pressure and flow rate gages. The drain solenoid valve on the top of the fuel tank should open, permitting the liquid on both sides of the fuel cell to drain into the fuel tank.

    c. Turn the fuel tank heater switch to the OFF position. Turn the thermostat to the COOL end of its range. (Clockwise).

    d. Open the Gas Flow Valve, permitting an increased gas flow rate to purge moisture from the fuel cell. Continue this for approximately two minutes.

    e. Turn the main valve on the gas tank to the CLOSE position. Back out the regulator valve on the gas tank. The oxygen source pressure and flow-rate should go to zero.

    f. Turn OFF the auxiliary panel power switch.

    g. Turn OFF the main power (115 volt) switch.

    h. Unplug the Fuel Cell Research System from the 115

volt supply.

i. CLOSE the Gas Flow Valve.

j. Place <u>all</u> valves in the pneumatic (gas) circuitry in the OFF or CLOSE position.

k. Turn the transducer input switch to the OFF position.

l. The voltmeter will continue to show a voltage. This is normal, as chemical reaction will result from oxygen and hydrazine remaining in the porous electrodes.

m. Remove and store any test equipment not intended for use in the near future.

n. All valves should now be in the OFF or CLOSED position. All switches on the fron panel should be in the OFF position. Check this.

o. Examine the entire cart for leaks of the liquid circuitry. If evidence of a leak is found, initiate steps immediately to fix it. Neutralize any spillage by wiping with a cloth or paper towel wetted with dilute acetic acid. DANGER. KOH and N_2H_4 LEAKS CAN CAUSE SERIOUS SKIN BURNS AND CORROSION OF PAINT AND EQUIPMENT.

p. FILL IN ALL NECESSARY DATA IN THE OPERATION LOG. THIS IS ESSENTIAL FOR MAINTENANCE AND FOR DETERMINING THE AGE OF THE FUEL BATCH IN THE FUEL TANK.

q. IF SYSTEM IS NOT TO BE USED OR RUN FOR MAINTENANCE PURPOSES WITHIN THE NEXT TWO WEEKS, CARRY OUT PRO-

CEDURE FOR STORAGE SHUT-DOWN. [9]

r. Check to see that the stand is free from all lines.
    Remove wheel brake. Return stand to storage posi-
    tion in an OPEN OR WELL VENTILATED SPACE. Reapply
    wheel brake.

s. Insure that the tops of all chemical storage
    bottles are tightly closed.

D4. Storage Procedure:

    a. This procedure should be followed whenever the Fuel Cell Research System is not to be used and maintenance runs cannot be held. Maintenance runs should be about 10-15 minutes twice a week. At a maximum if a maintenance run cannot be held for 2 weeks, this procedure should be carried out.

    b. Carry out the normal shut-down procedure. After step (e) of the shut-down procedure, carry out the following.

    c. Remove the fuel from the fuel tank. NEUTRALIZE THE FUEL TANK CONTENTS WITH DILUTE ACETIC ACID BEFORE DISPOSING OF IT. Close the drain valve.

    d. Remove filling inlet plug. Fill fuel tank with six liters of distilled water. Replace filling inlet plug.

    e. Set up pneumatic circuitry to provide the fuel cell with a nitrogen gas input.

    f. Turn main power switch to ON position.

    g. Admit nitrogen gas to the fuel cell, at 2 psig, flow meter reading of 8.

    h. Turn the fuel pump motor controller to full voltage position.

    i. Turn the fuel pump motor to the ON position. Observe liquid pressure of 1-3 psig and flow rate meter reading of at least 6.

    j. Run the system in this condition for about 10

minutes. Check the fuel cell output voltage. It should fall to zero indicating complete usage of all hydrazine and oxygen in the porous electrodes. The system should be run for about 5 minutes after the output voltage is observed to be zero.

k. Turn the fuel pump motor switch to the OFF position.

l. Turn the main power switch to the OFF position and unplug the system for the 115 volt supply.

m. Turn the main valve of the nitrogen gas tank to CLOSE position, back off the regulator, and put all pneumatic circuitry valves in the CLOSE or OFF position. Close the Gas Flow Valve.

n. Empty the fuel tank of all liquid.

o. Carefully disconnect all liquid and gas inputs to the fuel cell. CAUTION. SOME CAUSTIC MATERIAL MAY REMAIN. WIPE UP ALL SPILLS WITH RAG WETTED WITH DILUTE ACETIC ACID.

p. Insure that the fuel cell electrical output terminals have no load across them.

q. Securely cap all fuel cell openings to prevent drying out.

r. Neutralize the contents of the air scrubber, the fuel tank exhaust scrubber, and the oxygen source output byproduct collector with dilute acetic acid. Remove the air scrubber and the two bottles, dispose of their contents, rinse with distilled

water, and replace on the stand.

s. Secure all equipment.

To reactivate the System:

a. Reconnect all of the inputs to the fuel cell.

b. Check all tubes and fittings for tightness.

c. Refill the fuel tank exhaust scrubber and the by-product collector with dilute acetic acid. (About 5 per cent) Fill the air scrubber to one inch depth with 45 per cent KOH.

d. Carry out normal light-off procedure. BE WARY OF LEAKS WHEN REACTIVATING.

D5. <u>Chemical Mixing Instructions and Safety Precautions</u>:

Care should be taken to avoid skin contact with any fuel cell chemicals. A standard fuel mixture of 10 per cent hydrazine and 33 per cent potassium hydroxide (10-33 Mixture) can be obtained as follows: Into a one liter container, measure 160 ml (millimeters) of 64 per cent hydrazine solution, 740 ml of 45 per cent potassium hydroxide solution, and 100 ml of distilled water.

The 64 per cent hydrazine solution and the 45 per cent potassium hydroxide solution are standard mixtures and are commercially available from Matheson Scientific,Inc.,24800 Industrial Blvd., Hayward, California:

Item	Unit Issue	Number	Price Estimate
1. Potassium Hydroxide,Reagent, 45% solution	8 pints	PX1488,CB1150	$8.64
2. Hydrazine, Practical, 64% in water	500 grams	HX541,P6759	$7.20

It requires approximately 8 pints of the potassium hydroxide solution and 500 grams of the hydrazine solution to mix one 5 liter fuel batch (10-33 Solution).

Other mixtures can be obtained by computing the per cent by volume of each ingredient.

EXAMPLE: 10-33 Fuel Batch

160 ml x .64 = 102 ml pure N_2H_4

160 ml x .36 = 58 ml H_2O

740 ml x .45 = 332 ml pure KOH

740 ml x .55 = 408 ml H_2O

$$\underline{ 100 \text{ ml } H_2O}$$

1000 ml = Total Volume

$$\%_H = \frac{102}{1000} \times 100 = 10.2\%$$

$$\%_E = \frac{332}{1000} \times 100 = 33.2\%$$

A table of one liter batches convenient for examining the effect of changing %H and %E is shown below.

Fuel Batch	ml of 64% N_2H_4 solution	ml of 45% KOH solution	ml of distilled H_2O
5-33	78	740	172
10-33	160	740	100
15-33	235	740	25
5-20	78	445	477
10-20	160	445	395
15-20	235	445	320

CHEMICAL SAFETY PRECAUTIONS: The following precautions should be taken when handling fuel cell chemicals:

   a. Work in an open or ventilated space.

   b. Wear eye protection, rubber gloves and a rubber apron.

   c. Work near a sink with running water.

d. Avoid skin contact with fuel cell chemicals. KOH
    can cause dangerous burns. N_2H_4 can also cause
    burns. N_2H_4 is toxic and has an accumulative ef-
    fect. Neither is dangerous if washed off immedia-
    tely. <u>Both chemicals are bases and can be washed</u>
    <u>away quickly with a towel wetted with dilute ace-</u>
    <u>tic acid (vinegar) accompanied by flushing thor-</u>
    <u>oughly with water</u>. Any contact with the eyes or
    open cuts may be more dangerous. Flush the area
    thoroughly as described and consult a doctor imme-
    diately if this occurs.

e. Avoid sniffing fumes, as they are toxic. Use a
    fan to blow fumes away from mixing area.

f. Pour carefully and insure that all chemical bottles
    are tightly closed immediately after use.

g. THE ANTIDOTE FOR INTERNAL HYDRAZINE POISONING IS AS
    FOLLOWS: Give a tablespoon full of salt in warm
    water to induce vomiting. Cause vomiting until
    the liquid is clear. Give one ounce of charcoal
    (burnt toast). Mix and give the "Universal Anti-
    dote" as follows:

        2 parts charcoal (burnt toast)

        1 part tannic acid (strong tea)

        1 part magnesium oxide (milk of magnesia)
        Mix together in warm water.
        CALL A DOCTOR IMMEDIATELY.

h. THE ANTIDOTE FOR INTERNAL POTASSIUM HYDROXIDE POI-

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SONING IS AS FOLLOWS:

Give large amounts of vinegar or citrus juices.

Follow with olive oil.

CALL A DOCTOR IMMEDIATELY.

i. FOR EYE CONTACT WITH EITHER CHEMICAL:

Wash immediately with very large amounts of fresh
water. Wash with a 5 per cent boric acid solution.
CALL A DOCTOR IMMEDIATELY.

j. FOR SKIN CONTACT WITH EITHER CHEMICAL:

Wash immediately with very large amounts of fresh
water. Flush the area with dilute acetic acid (vin-
egar). Wipe away the "slippery" base with a towel
wetted with dilute (5 per cent acetic acid or vin-
egar. CALL A DOCTOR IF CONTACT OVER A LARGE SKIN
AREA IS MADE, OR IF STINGING OR BURNING SENSATION
PERSISTS.

Hydrazine in the fuel batch is used at the rate of 47
ml per hour per cell for a current load of 75 amperes. Wa-
ter is produced as a byproduct of the chemical reaction at
the rate of 45 ml per hour per cell for the same load cur-
rent. The fuel battery in the Fuel Cell Research System
contains 4 cells. (See Figure 4). [9]

As the hydrazine in a fuel batch is used, the cell
voltage output will begin to decrease. This effect will be-
come noticeable after two to three hours of operation on
one six liter fuel batch. Hydrazine may be added to replen-
ish the system providing that %H does not exceed 15 per cent.

The high level warning light on the front panel will indi-
cate when the fuel tank level is too high. When this
light comes on, no further liquid should be added. Know-
ing the hours of operation on one fuel batch, the average
load current, and the rough values of hydrazine consump-
tion and water production, the amount of 64 per cent hydra-
zine which can be added to the fuel tank can be computed.
EXAMPLE: Six liters of 10-33 fuel solution have been in
for two hours at an average load current of 20 amps. How
many ml of 64 per cent hydrazine solution may be added such
that 10 < %H < 13?

$$- \frac{20}{75} \times 47 = -12.5 \text{ ml } N_2H_4/\text{cell/hr.}$$

$$- \frac{20}{75} \times 45 = +12.0 \text{ ml } H_2O/\text{cell/hr.}$$

For 6 liters of 10-33 fuel solution, there are 600 ml
of pure hydrazine in the initial solution.

$$600 \text{ ml} - 12.5 \frac{\text{ml}}{\text{cell-hr}} \times 4 \text{ cell} \times 2 \text{ hrs} = 500 \text{ ml}$$

There are 3420 ml of H_2O in the initial 6 liters of the
10-33 fuel solution.

$$3420 \text{ ml} + 12.0 \frac{\text{ml}}{\text{cell-hr}} \times 4 \text{ cells} \times 2 \text{ hrs} = 3516 \text{ ml}$$

The initial 6 liters of 10-33 fuel solution contained
1980 ml of pure KOH. This value should not be changed by
the fuel cell operation.

After two hours of operation, there are 500 ml of pure N_2H_4, 3516 ml of H_2O, and 1980 ml of pure KOH. Therefore,

$$\%H = \frac{500}{5996} \times 100 = 8.35\%$$

$$\%E = \frac{1980}{5996} \times 100 = 33.1\%$$

If 500 ml of 64 per cent N_2H_4 were added:

$$500 \times .64 = 320 \text{ ml pure } N_2H_4$$

$$500 \times .36 = 180 \text{ ml } H_2O$$

$$\%H = \frac{500 + 320}{5996 + 500} = \frac{820}{6496} = .126 \text{ or } 12.6\%$$

$$\%E = \frac{1980}{6496} = .305 \text{ or } 30.5\%$$

REMARK:

A less accurate but faster way to approximate the N_2H_4 precentage is arrived at by noting that

$$\frac{amps}{75} \times 47 \times 4 \text{ cells} = 2.5 \frac{ml\ used}{amp\text{-}hours} .$$

Or (ml pure N_4H_4 used) = 2.5 x amp-hours; in a similar fashion, (ml H_2O produced) = 2.4 x amp-hours. Since these two factors are reasonably close, simply obtain the total "amp-hours" for the experiment, multiply by 2.5 and reduce the concentration of pure N_2H_4 by this amount, considering the total fuel amount unchanged.

EXAMPLE:

The average load for a two hour experiment was 10 amps the first hour and 20 amps the second hour. If the original fuel was 6 liters of 10-33, what is the % H at the conclusion?

Total amp-hours = 1 x 10 + 1 x 20 = 30 a-h

(ml pure N_2H_4 used) = 2.5 x 30 = 70 ml

Present %H = $\frac{600-70}{6000}$ x 100 = 8.83%

D6. Maintenance and Procurement:

In order to maintain the Fuel Cell Research System in proper working order, the following action should be taken.

a. Weekly Maintenance Runs: Light off the system and run it under loaded conditions for ten minutes. Use a load which will draw 10-15 amperes. This must be done a minimum of once a week, and preferably twice a week. If the system is run for an experiment, this is the equivalent of a maintenance run.

b. Weekly Field Day: Check the entire stand for moisture. Wipe up with a towel wetted with dilute acetic acid (5 per cent) or vinegar.

c. Weekly Circuit Check: Trace all circuits shown in Appendix D. Check for loose fittings on the liquid and gas circuitry. Check for grounds, shorts, or dangerous wire exposures in the 115 volt electrical circuit as well as the fuel cell output circuit. Keep the system free of excess equipment or tools which may interfere with its operation.

d. If the system is not to be used for a period of two weeks or more, carry out the storage shut down procedure found in Section 3 of Appendix D.

e. Quarterly Cleaning of Electrodes: The storage shut-down procedure found in Section 3 of Appendix D should be carried out at least once every three months. This causes a purging of all active che-

micals from the system.

f. If the fuel cell electrodes become excessively exposed to air while the cell is not in operation, it will cause a coating of the electrodes. This may occur after a storage period. This coating will result in a reduced fuel cell power output. It will correct itself by running the system normally. If the rated power cannot be obtained after ten hours of operation, investigate other causes of reduced power.

g. The 45 per cent KOH solution in the air scrubber should be replaced after ten hours of use, and at least once a quarter.

h. The dilute acetic acid solution (5 per cent) in the fuel tank exhaust scrubber and the byproduct collector should be replaced after ten hours of operation, and at least once a quarter.

i. It is important not to let excess moisture collect in the fuel cell. Thus, purging, or blowing gas through the fuel cell before and after each operation, is part of the operating procedure. If excess moisture is noted in the oxygen source outlet, blow oxygen through the fuel cell and force this moisture into the byproduct collector. This will be a part of the weekly maintenance run. However, it can be done without lighting off the entire system if excess moisture is noted.

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j. Trouble-Shooting: The Fuel Cell Instruction Manual contains procedures for trouble-shooting.[9] The following gentleman was helpful in correspondence concerning the system.

> Mr. Eugene Revolinsky
> Manager, Application Services
> Research Division
> Allis-Chalmers
> Box 512
> Milwaukee, Wisconsin 53201

k. Operators should be thoroughly familiar with the Fuel Cell Instruction Manual. [9] CONSISTENT AND ACCURATE ENTRIES IN THE OPERATORS LOG ARE ESSENTIAL TO PROPER MAINTENANCE.

l. A list of equipment making up the Fuel Cell Research System is found in Appendix I of the Fuel Cell Instruction Manual. [9] The following items of this list were not used:

Mechanical System (6), (10), (12), (13) and (14).

Electrical Components (2), (6), (12) and (13).

All meters, shunts, and resistors were obtained from on hand items. Materials may be ordered from:

> Allis-Chalmers
> Box 512
> Milwaukee, Wisconsin 53201

m. The current-pressure transducer was obtained from the Foxboro Company. [10] Parts and other types of control valves may be ordered from:

The Foxboro Company
399 Preda Street
San Leandro, California 94577

Another source of control valve is:

Fisher Governor Company
Marshalltown, Iowa 50158

The current-pressure transducer cover should be removed occasionally and the parts cleaned. See the Foxboro Instruction Manual for adjustment and calibration procedures. [10]

n. The brass and nylon fittings, polyethylene tubing, and rubber tubing was manufactured by:

Imperial Eastman Corporation
6300 W. Howard Street
Chicago, Illinois

This corporation's products are handled by the California Equipment Company, San Francisco, California. Some of the items can be purchased locally at Peninsula Auto Parts, Monterey, California, and orders can be placed there for items not in stock.

o. Other materials used include:

Stainless steel tubing

Teflon tape for sealing fittings and joints

Pyrex bottles, obtained from the Chemistry Department

Hose clamps, obtained at Peninsula Auto Parts.

p. The stand and associated fittings were constructed by Mr. Frank B. Abbe, Machinist, of the Naval Post-

graduate School, Machine Facility. This Facility
should be contacted for repairs or construction of
parts required in further experiments.

q. SAFETY NOTE: WHEN TROUBLE-SHOOTING FOR FUEL LEAKS,
WEAR EYE PROTECTION, RUBBER GLOVES AND RUBBER
APRON TO PROTECT AGAINST CHEMICAL SPILLAGE.

D7. Operation Log:

The Operation Log should be a three ring, loose-leaf
binder with the following sections:

a. A list of personnel checked out in operating the
system.

b. A copy of Appendix D of this thesis.

c. A copy of the Allis-Chalmers Fuel Cell Instruc-
tionManual.

d. An operation record kept on pages which are copies
of Figure D-1. One such page should be filled out
for each time the system is operated.

e. A maintenance log, kept on plane lined paper. It
should be a chronological record of casualties,
major maintenance items, and general items of in-
terest. Weekly maintenance runs need not be enter-
ed, but any storage procedure carried out should
be noted.

The Operation Log should be reviewed periodically by
the student using the system for a project, or by the Pro-
fessor responsible for the system.

Date:_____ __ Start:_____ Stop:_____ Hours:_____

Total Fuel
Cell Hours:_____ Fuel Batch:_____ Date Mixed:_____

Fuel Changes   No Change......
Today: Mixed New
  (check one)   Batch............ ____ml N_2H_4____mlKOH____ml H_2O
                  Added N_2H_4..... ____ml

Fuel Depletion   Total amp-hours x 2.5 =_____ml pure N_2H_4
Today.
Mixture at end
of run:_____

General Cell Performance:
 1.On a gas input of____,P_2=____psi, flow =_____cc/min

   the open circuit voltage was_____.

 2.Maximum attainable load was_____amps at_____

   volts(_____watts).

Remarks:

Cell Maintenance Held Today: (check)

____Routine weekly mainte-   ____Placed cell in storage.
    nance run.
____Renewed 5% Acetic Acid   ____Recalibrated Transducer.
    in beakers.
____Renewed KOH in scrubber   ____Purged cell with N_2 and
    (10 hrs.).   distilled water (3 mos.)

                                  _____
                                  Signature of Operator

Figure D1

FUEL CELL OPERATING RECORD

D8. Recommended Laboratory Exercises

    a. Fuel Cell Chemical Parameter Analysis:

        Observe the fuel cell output voltage as the following chemical parameters are varied individually

        1) Fuel temperature

        2) Air pressure

        3) Air-Flow rate

        4) Percent Oxygen in gas mixture

        5) Percent Hydrazine in the fuel mixture

        6) Percent Electrolyte in the fuel mixture

    b. Fuel Cell Load and Internal Resistance Analysis:

        With the fuel cell chemical parameters constant vary the resistive load, recording load voltage, current and power. From the resulting curve, observe the point of maximum power, and the fuel cell internal resistance. These readings can be recorded for various flow rates, gas composition, and percent hydrazine.

    c. Fuel Cell Frequency Analysis:

        With a small fixed load, vary the gas pressure or the percent oxygen with a sinusoidal input to the transducer. Record fuel cell output voltage on a trace recorder. The open loop frequency response, magnitude and phase, can be plotted.
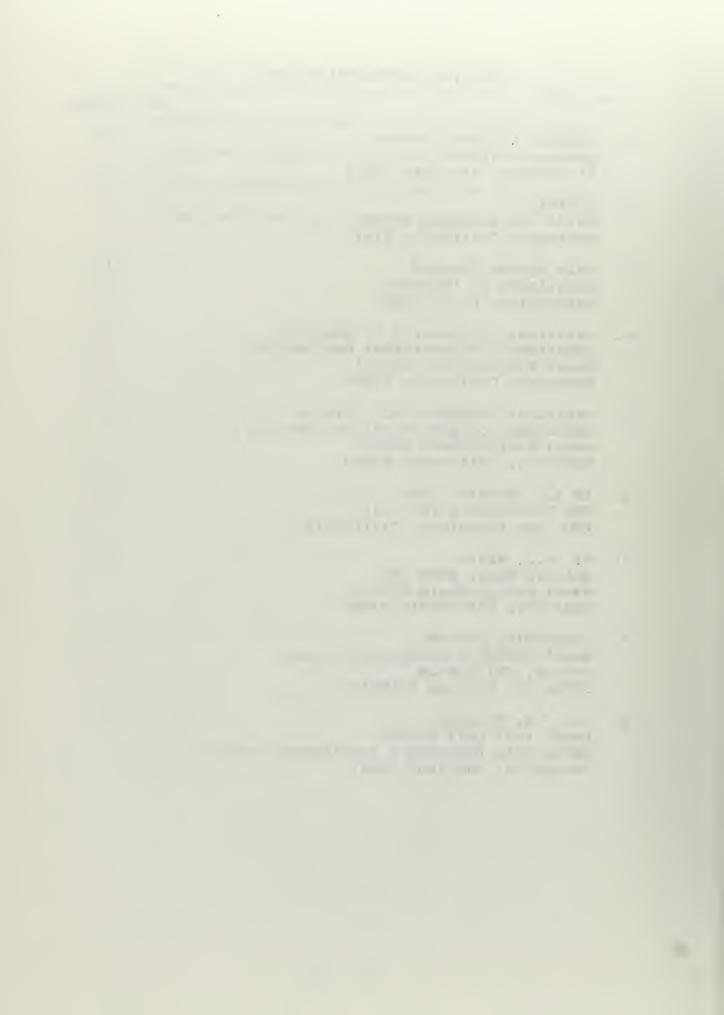
    d. Fuel Cell Transient Analysis:

        With all chemical parameters constant and a

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small resistive load on the fuel cell, step in-
crease the gas pressure or the percent oxygen
with the voltage to the transducer. Record the
output voltage on a trace recorder for various
size positive and negative steps.

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DOCUMENT CONTROL DATA - R & D

Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Naval Postgraduate School Monterey, California 93940	UNCLASSIFIED
	2b. GROUP

3 REPORT TITLE

EXPERIMENTAL DESIGN FOR CONTROL OF THE HYDRAZINE-OXYGEN FUEL CELL

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

M. S. Thesis - Electrical Engineering - 1968

5. AUTHOR(S) (First name, middle initial, last name)

Robert J. Brenton
Lieutenant, United States Navy

6 REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
September 1968	79	14
8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)	
b. PROJECT NO.		
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
d.		

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
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13. ABSTRACT

    The control of output voltage of an experimental hydrazine-oxygen fuel cell is investigated. A mixture of nitrogen and oxygen is introduced into the cathode cavity, and the percentage of oxygen is varied to control the output voltage. After dynamic testing, a typical response is defined, and a feedback control system designed to improve transient response. The control scheme is evaluated using a digital computer to simulate the simplified plant model and the controller.

DD FORM 1473 (PAGE 1)
1 NOV 65

S/N 0101-807-6811

A-31408

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Fuel Cell						
Hydrazine						
Oxygen						
Control						
Dead time						
Predictor						

DD FORM 1473 (BACK)
1 NOV 65
S/N 0101-807-6821
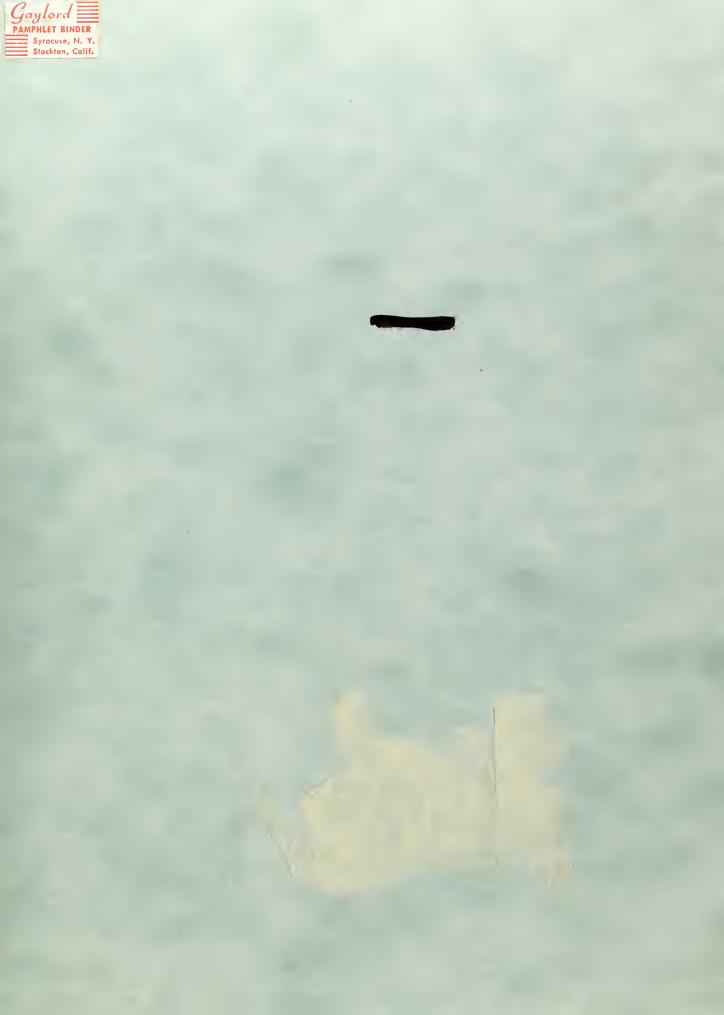
UNCLASSIFIED
Security Classification

A-31409

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